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### Interdiffusion, Crystallinity and Exchange Bias in $\text{Mn}_x\text{Pt}_{1-x}/\text{Co}$ Bilayers

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#### Abstract

The structure of the antiferromagnet (AF) in the Ta/ $\text{Mn}_x\text{Pt}_{1-x}$ /Co/Ta system must have the face-centered tetragonal CuAu structure in order to obtain a measurable exchange bias ( $H_E$ ). The formation of this structure has an onset temperature of approximately 240 °C. Increasing the annealing temperature increases the amount of CuAu ordering, which increases  $H_E$ , and also increases the MnPt/Co interdiffusion, which decreases  $H_E$ . These two competing processes result in an optimum annealing temperature that maximizes  $H_E$ .

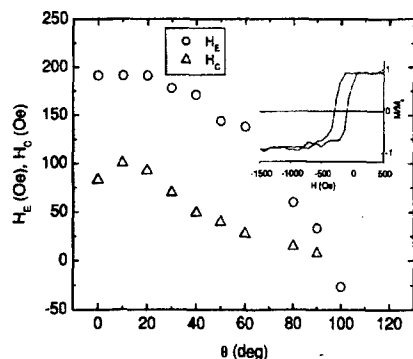
#### Introduction

The exchange bias anisotropy, discovered by W.H. Meiklejohn and C.P. Bean [1], is due to the coupling of an antiferromagnet (AF) and a ferromagnet (F). This unidirectional anisotropy effectively pins the F when the AF is below its Neel temperature ( $T_N$ ). This effect has applications in magnetic sensors and magnetic random access memory [2].

In this study we address the formation of the crystalline structure for the AF and quantitatively show that the interdiffusion at the AF/F boundary decreases the coupling.

#### Experimental Details

The samples were grown in a vacuum chamber at a base pressure of  $6 \times 10^{-7}$  Torr using magnetron sputtering. Separate targets for each material were used and the  $\text{Mn}_x\text{Pt}_{1-x}$  alloy was

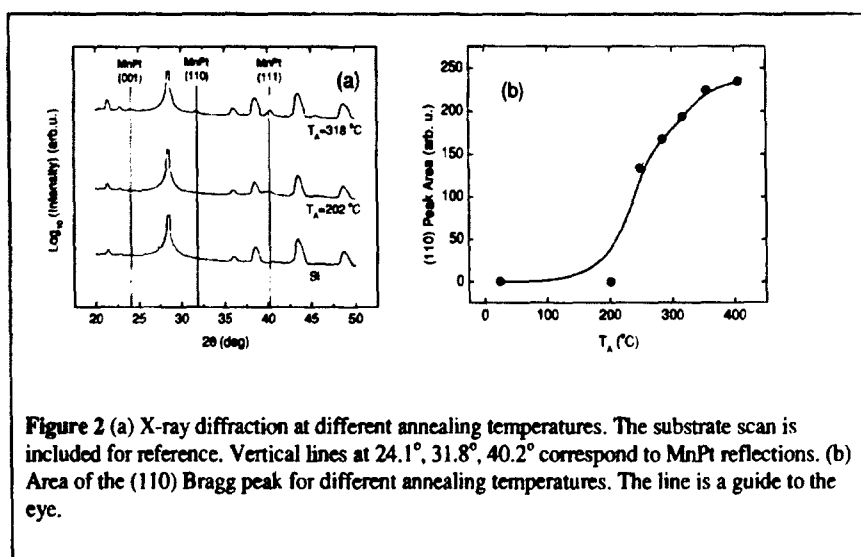


**Figure 1** Exchange bias ( $H_E$ ) and Coercivity ( $H_C$ ) as functions of angle measured from the setting field direction. The sample Mn concentration is  $x = 0.48$  and the annealing temperature  $T_A = 318$  °C. Inset is the MH loop for  $\theta = 0$ .

co-sputtered. Si (111) substrates were degreased without removing the native oxide layer. Typical sample structures consisted of Ta(10nm)/Mn<sub>5</sub>Pt<sub>1-x</sub>(25nm)/Co(8nm)/Ta(20nm). The Ta capping layer was used to prevent oxidation and degradation of the sample. X-ray rocking curves indicated that the as-grown samples were polycrystalline. We post-annealed the samples at different temperatures in a magnetic field in order to obtain an appreciable  $H_E$ . The annealing procedure consisted of ramping to the desired temperature in 20 minutes and then waiting one hour for stabilization. A 1200 Oe permanent magnet was then placed underneath the sample and left there during the annealing time. This was done in order to align the AF in the field direction so that after the temperature is lowered the F is pinned. Samples were characterized by x-ray diffraction and reflectivity using a rotating anode attached to an 18 kW power supply and Cu K $\alpha$  radiation ( $\lambda \sim 0.1542$  nm).

$H_E$  was determined from the shift of the magnetic hysteresis loops away from  $H = 0$  using the magneto optical Kerr effect (MOKE). A typical MOKE result for different angles with respect to the direction of the applied field during annealing is shown in Figure 1. The loop is not symmetric, in agreement with the model proposed by D. Mauri et al. [3] where a domain wall is formed in the AF during domain reversal in the F.

The annealing procedure was performed only once on each sample. The interface interdiffusion was determined with a computer program [4] that recursively calculates the x-ray reflection coefficient of each layer from top to bottom adding a grading at the AF/F layer where the index of diffraction varies linearly from the AF value to the F value.



**Figure 2** (a) X-ray diffraction at different annealing temperatures. The substrate scan is included for reference. Vertical lines at  $24.1^\circ$ ,  $31.8^\circ$ ,  $40.2^\circ$  correspond to MnPt reflections. (b) Area of the (110) Bragg peak for different annealing temperatures. The line is a guide to the eye.

## Results and Discussion

Conventional wisdom holds that the annealing temperature ( $T_A$ ) has to be greater than  $T_N$  in order to obtain  $H_E$ . In this case, however, this is not necessary, presumably due to the low magnetic anisotropy of the AF. Figure 2 (a) shows that the onset of the CuAu structure is not complete at  $T_A = 202$  °C, while the  $T_A = 318$  °C sample shows the MnPt (110) reflection. This reflection can only occur for the ordered CuAu structure. According to Krén et al. [6], the  $T_N$  for this concentration of  $x = 0.48$  is 682 °C. In order to quantify the amount of CuAu structural ordering, the area of the (110) reflection was measured for each annealing temperature. The area grows monotonically throughout the entire temperature range and at  $T_A = 406$  °C seems to be close to its maximum, as shown in Figure 2 (b). This is important because the exchange bias also should have increased in the same temperature range if it only had been proportional to the amount of CuAu ordering. The exchange bias, however, peaked at  $T_A = 318$  °C, as shown in Figure 3. Hence, there must have been other factors that contributed to the decrease at higher annealing temperatures.

X-ray reflectivity results qualitatively show a loss of sharp interfaces as  $T_A$  is increased, as shown in Figure 4. In the as-grown sample there are high frequency peaks, corresponding to the total thickness of the sample, modulated by a low frequency signal, corresponding to the individual layer thicknesses. This low frequency modulations for the most part are absent for the sample annealed at  $T_A = 407$  °C. This means that the interfaces become less well pronounced as the annealing temperature increases. This was verified by the fit to the spectra shown in Figure 4. The results for the interdiffusion roughness for the MnPt/Co interface ( $\sigma_{\text{MnPt/Co}}$ ) are shown in Figure 5. The sample with the maximum  $H_E$  has an interdiffusion of  $\sigma_{\text{MnPt/Co}} = 1.4$  nm. This amount of roughness might at first sight seem excessive, but it is consistent with the results of

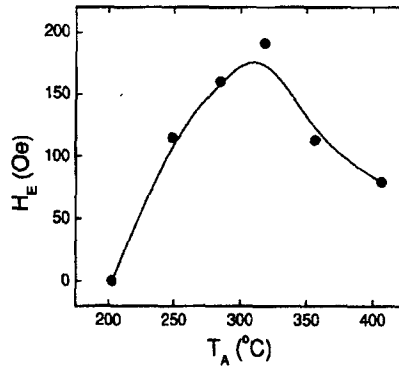


Figure 3 Exchange bias as a function of annealing temperature for nominally identical samples.

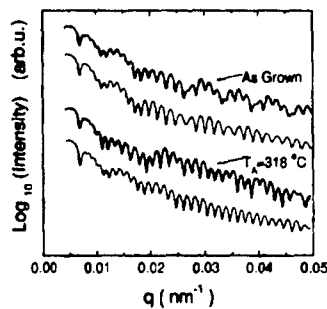


Figure 4: X-ray reflectivity for as-grown and  $T_A = 318$  °C samples with their corresponding fits below are shown.

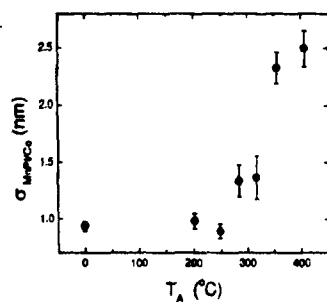


Figure 5: Roughness at the AF/F interface as a function of annealing temperature determined from x-ray reflectivity modeling.

Honda et al., who measured an appreciable  $H_E$  in MnPt/FeCo with up to 2 nm of Ag placed at the AF/F interface [7]. Furthermore, the fits showed that increasing the roughness parameters of all the other interfaces did not reproduce the measured spectra and did not increase systematically as the annealing temperature ( $T_A$ ) was increased [8]. This indicates that most of the interdiffusion occurs at the MnPt/Co interface.

## Conclusions

Our results indicate that there is a minimum temperature required to obtain the CuAu ordered structure. Below this temperature the crystalline ordering does not provide the correct antiferromagnetic structure and the measured  $H_E$  is zero. For greater annealing temperatures the amount of CuAu structural order increases and saturates above 400 °C. However, the exchange bias peaks at 318 °C because of increasing interdiffusion at the MnPt/Co interface, which presumably weakens the AF/F exchange coupling. These results indicate that the exchange bias could be increased further if the interdiffusion could be suppressed during the annealing procedure.

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